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Research Report

When does perceptual organization happen?

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ABSTRACT

Reflectional (mirror) symmetry is an important visual cue for perceptual organization. The brain processes symmetry rapidly and efficiently. Previous work suggests that symmetry activates the extrastriate cortex and generates an event related potential (ERP) called the ***Sustained Posterior Negativity*** (SPN). It has been claimed that no tasks completely block symmetry processing and abolish the SPN. We tested the limits of this claim with a series of eight new Electroencephalography (EEG) experiments (344 participants in total). All experiments used the same symmetrical or asymmetrical dot patterns. When participants attended to regularity in Experiment 1, there was a substantial SPN (Mean amplitude = −2.423 μV). The SPN was reduced, but not abolished, when participants discriminated dot luminance in Experiments 2 and 3 (−.835 and −1.410 μV) or the aspect ratio of a superimposed cross in Experiments 4 and 5 (−.722 and −.601 μV). The SPN also survived when the background pattern was potentially disruptive to the primary task in Experiment 6 (−1.358 μV) and when participants classified negative superimposed words in Experiment 7 (−.510 μV). Finally, the SPN remained when participants attended to the orientation of a diagonal line in Experiment 8 (−.589 μV). While task manipulations can turn down the extrastriate symmetry activation, they cannot render the system completely unresponsive. Permanent readiness to detect reflectional symmetry at the centre of the visual field could be an evolved adaptation.

1. Introduction

Reflection a is salient form of visual symmetry for humans (Mach, 1886). Reflectional symmetry was identified as a grouping factor by Gestalt psychologists and serves as an important visual cue that aids perceptual organization (Mojica & Peterson, 2014; Pomerantz & Kubovy, 1981; Wagemans et al., 2012). Symmetry also guides mate and food selection in many species (Møller, 1992).

The neural response to visual symmetry has been studied for the last two decades (Bertamini et al., 2018). Functional MRI studies have consistently found that visual symmetry activates a network of regions in the extrastriate cortex (Chen et al., 2007; Keefe et al., 2018; Kohler et al., 2016; Sasaki et al., 2005; Tyler et al., 2005; Van Meel et al., 2019). The

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extrastriate symmetry response scales with the proportion of symmetry in mixed symmetry + noise patterns (a variable called 'pSymm'), and with the degree of regularity in an abstract geometrical set known as the 'wallpaper patterns' (Audurier et al., 2022; Kohler & Clarke, 2021; Kohler et al., 2016).

The extrastriate symmetry response can be measured with EEG. After the P1 and N1 components of the visual evoked potential, ERP amplitude is lower at posterior electrodes when participants view symmetrical compared to asymmetrical images (Jacobsen & Höfel, 2003). This symmetry–asymmetry difference wave is called *Sustained Posterior Negativity* (Makin et al., 2012). Like the fMRI response, SPN amplitude also scales with pSymm (Fig. 1A). The SPN is reduced, but not abolished, when participants attend to other stimulus features, such as colour or sound (Makin et al., 2020; Tyson-Carr et al., 2021).

Visual symmetries vary in terms of *perceptual goodness* – a term from Gestalt psychology which refers to the salience of a visual configuration. Perceptual goodness can be coded with the *holographic weight of evidence model* from van der Helm and Leeuwenberg (1996). This provides a metric called the *W-load*, which ranges from 0 to 1. More obvious regularities have larger W-loads, and W-load predicts SPN amplitude (Makin et al., 2016).

We have recently analysed 40 SPN projects at the University of Liverpool, with 249 grand average SPNs from 2215 participants (Makin et al., 2022). Most (227) of these are shown in Fig. 1B. Bottom up (W) and top down (Task) predictors explain ~34% of the variance in SPN amplitude [SPN (μV) = −1.7 (W) −.4 (Task) + .1]. A full version of this regression analysis is provided in Supplementary materials 1, but two brief clarifications are important here. First, Task can be conceptualized as a continuous predictor that ranges from 0 to 1. Task = 0 means regularity was minimally task-relevant, and Task = 1 means regularity maximally task relevant. Task could set to some intermediate value such as .5 (e.g., if participants were attending to both regularity and colour on every trial). However, for this analysis, all experiments were coded as 0 or 1. Second, this equation does not include the interaction term, because it does not explain substantial additional variance. The additive effects of W and Task mean that the SPN is often absent when Task = 0 and W is <.5. Meanwhile the SPN is nearly always present when Task = 0 and W > .6. Indeed, we only know one exception, from an experiment where participants attended to negative superimposed words, such as "hate" and "death" (Rampone et al., 2014, highlighted with < in Fig. 1B). This exception notwithstanding, perceptual grouping by symmetry appears preattentive and automatic when W is ≥.6.

The current project was designed to test the apparent automaticity of high W symmetry detection with the most rigorous series of experiments yet. Are there untried tasks which make the brain blind to symmetry, and abolish the

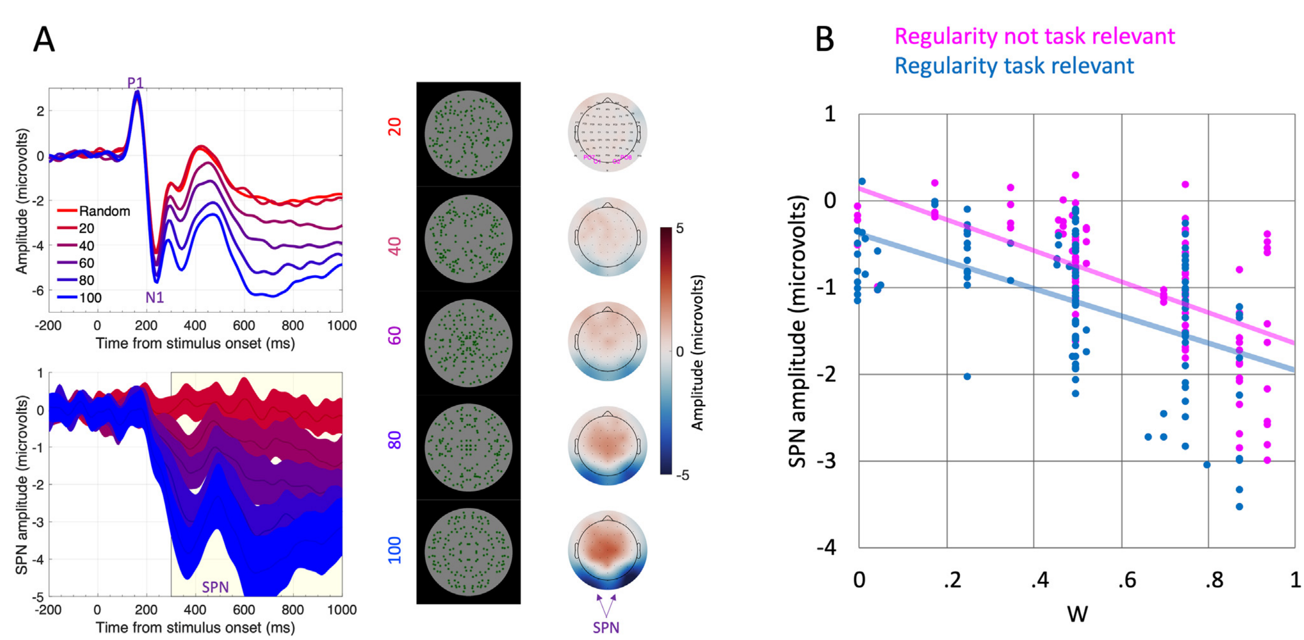

Fig. 1 – A) The parametric response to visual symmetry from Makin et al. (2020). ERPs from posterior electrode cluster [PO7, O1, O2 and PO8] are shown in the top panel, and difference waves with 95% CI ribbons are shown in the bottom panel. On the right there are topographic difference maps aligned with example stimuli. These show SPN amplitude as blue at posterior electrode clusters. B) Scatterplot of SPNs in the complete Liverpool SPN catalogue (https://osf.io/2sncj/). SPN amplitude increases with symmetry salience (W). SPN Is also increased when Regularity is task relevant (blue dots). There is only one task where high W stimuli did not generate an SPN (highlighted with an < symbol). The current project tested the apparent automaticity of high W symmetry processing with eight new experiments. Figure adapted from Makin et al. (2022).

SPN? This speaks to a more fundamental research question: How much perceptual organization happens preattentively? This is a foundational topic in vision science, addressed in a classic book by Mack and Rock (1998). One of our experiments adopted the inattentional blindness manipulation made famous in this line of research.

We conducted 8 experiments, beginning with a regularity discrimination task. This generated a large SPN (Experiment 1). We then found that there was still an SPN during easy and difficult luminance discrimination tasks (Experiments 2 and 3), during tasks known to cause inattentional blindness (Experiment 4 and 5), during a task where symmetry was potentially distracting (Experiment 6), a task where participants attended to negative superimposed words (Experiment 7) and a line orientation discrimination task that might inhibit representation of the axes (Experiment 8).

All data, experimental presentation codes, preregistration reports and supplementary materials are available on Open Science framework, alongside the rest of the SPN catalogue (Project 41 at https://osf.io/2sncj/).

2. General methods

2.1. *Apparatus*

All EEG experiments used the BioSemi Active-Two system (Amsterdam, Netherlands). EEG data was recorded continuously from 64 scalp electrodes arranged according to the extended international 10–20 system. Bipolar VEOG and HEOG external channels were used to monitor for ocular artifacts, but not included in ERP analysis. Participants were positioned 57 cm from a 51 × 29 cm (1920 × 1080 pixel) HP E233 LED backlit monitor, with 60 Hz refresh rate. Head position was stabilized with a chin rest. All experiments were conducted in the same electrically shielded and darkened room. Experiments were programmed in Python using open source PsychoPy software (Peirce, 2007).

2.2. *Stimuli*

All patterns were arrangements of 40 Gaussian filtered dot elements in a square frame at the centre of the screen (Fig. 2). The square was 6.6 × 6.6 cm, and thus approximately 6.6 × 6.6 degrees of visual angle (dva). This square had an implicit grid of 12 × 12 cells (Fig. 2B). The central 10 × 10 grid was populated with small dots, each approximately .25 dva in diameter. Each quadrant had 10 dots, occupying 40% of the available 25 cells. In the first quadrant the occupied cells were chosen randomly (purple in the diagram in Fig. 2B). Within each occupied cell, dot location was jittered on the X and Y dimensions by approximately ±.1 dva, so it was rarely located at cell centre. This intra-cell jittering prevented the appearance of multi-element straight lines spanning several cells. Without intra-cell jittering, even the asymmetrical patterns had rows and columns of aligned elements. For symmetrical patterns, the first quadrant was reflected three times, giving 2-fold vertical plus horizontal reflection (with a W-load of .75). For asymmetrical patterns, all four quadrants were generated independently. Symmetrical and asymmetrical stimuli were indistinguishable based on information in a single quadrant. At centre, the dots were either black

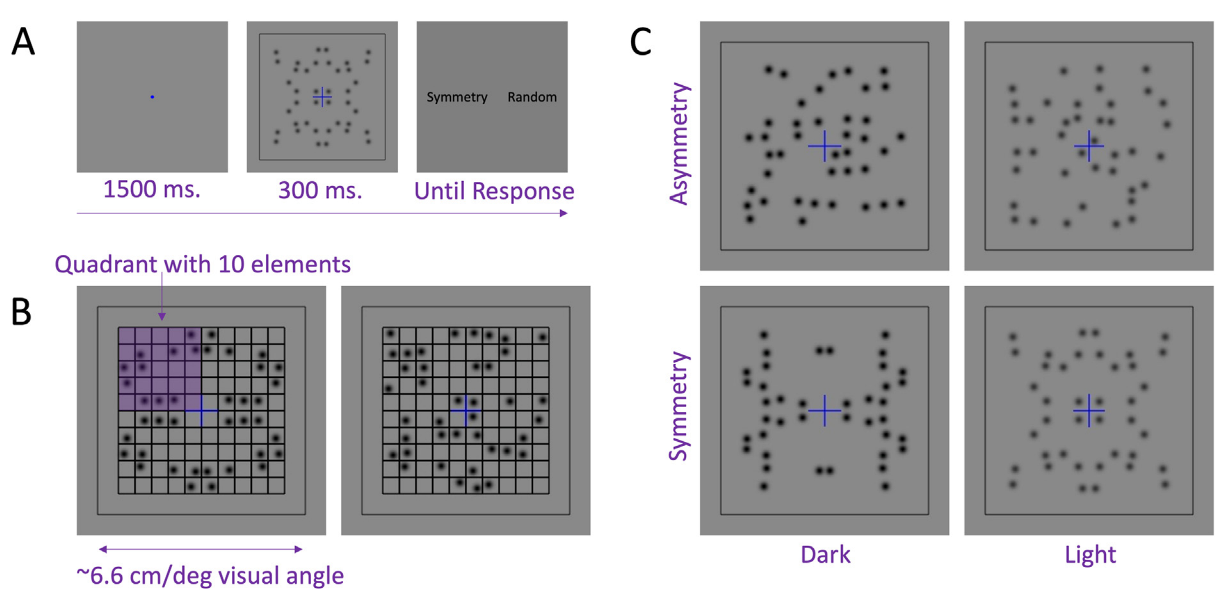

Fig. 2 – Trial structure and stimulus design. A) Trial structure. Each stimulus was presented for 300 msec following a 1500 msec baseline. In different experiments participants made a different classification. For example, in Experiment 1, participants classified patterns as 'Symmetry' or 'Random'. B) Stimulus construction algorithm. Each quadrant if the 10 × 10 grid had 10 dot elements (purple zone). For symmetrical patterns, quadrants were reflected twice, giving 2-fold horizontal and vertical reflection. For asymmetrical patterns each quadrant was independent. C) Example stimuli from symmetry and asymmetry X dark and light conditions.

(approximately .1 cd/m^2) or dark grey (4 cd/m^2). The background was mid grey (approximately 37 cd/m^2).

2.3. Procedure

All experiments used the same stimuli and basic design. All involved 320 critical trials, with 160 symmetrical patterns and 160 asymmetrical patterns. We increased the number of trials from our previous SPN projects to improve signal to noise ratio (following recommendations in Boudewyn et al., 2018).

Before each experiment participants completed 32 practice trials with the same distribution of conditions. Practice trials were not included in analysis.

On each trial, patterns were always presented for 300 msec, following a 1500 msec baseline (Fig. 2A). A small central fixation dot was present during the baseline, and participants were instructed to fixate and avoid blinks or eye movements during the baseline and stimulus intervals.

At the end of the experiment, participants were asked whether they noticed anything about the patterns other than the task relevant dimension. Some participants spontaneously reported noticing the regularity manipulation (for example, they might have said, "Yes, of course, some of the patterns were symmetrical", or words to that effect). Others reported ignorance (e.g., "No, I was just concentrating on the blue cross"). Others gave ambiguous initial reports, but their awareness was revealed by subsequent questioning (e.g., "Oh yes, I noticed that some were like shapes and faces, if that's what you mean"). The experimenters avoided leading questions (e.g., "Did you see the symmetry?") and used their discretion to classify each participant as having noticed the regularity manipulation or not. A minority of participants remained unclassifiable.

2.4. EEG processing

EEG data was analysed in eeglab 2022.1 in Matlab 2022b (Delorme & Makeig, 2004). First, datasets were re-referenced to the scalp average, low pass filtered at 25 Hz, and downsampled to 256 Hz (we have traditionally used 128 Hz downsampling in SPN analysis, but efficiencies in pre-processing have allowed us to improve temporal resolution). Continuous data was then segmented into −500 to +500 msec epochs. Noisy channels were then identified and zeroed during artifact rejection with Independent Components Analysis (ICA). Components representing large artifacts were identified and removed using the *Adjust* procedure, and then missing channels were replaced with spherical interpolation. This sequence reduces problematic interactions between interpolation and ICA cleaning. Finally, trials where amplitude exceeded ±100 μV at any scalp electrode were excluded (usually less than 10%). We then averaged over trials in each condition for each participant. Data from each pre-processing stage and pre-processing codes are available on open science framework (Project 41 in the complete Liverpool SPN catalogue, https://osf.io/2sncj/).

The SPN was defined as the symmetry−asymmetry amplitude difference averaged posterior electrode clusters [PO7 O1 O2 and PO8] and across the 250–400 msec interval. This spatiotemporal cluster was chosen a-priori and preregistered. However, in some experiments, the SPN peaked within the 250–400 msec interval, so we ran additional analysis is with a post hoc interval.

2.5. Power analysis

The decision to collect at least 40 participants in each experiment was based on analysis of the SPN catalogue and recommendations in Makin et al. (2022). First, we considered power of within-subject effects. Analysis of the SPN catalogue suggests that −.5 μV SPNs have an average Cohen's d_z of −.469. A sample of 40 participants provides the conventionally adequate threshold of 80% power for finding an effect of this size with a one sample t test (alpha .05, two tailed). In other words, if an experimental condition generates a relatively small mean SPN of −.5 μV, we have a reasonable chance (80%) of finding a significant effect ($p < .05$). Second, we considered power of between-subject effects. When participants attend to two-fold reflectional symmetry in Experiment 1, we can expect an SPN of at least 1.5 μV. Experiment 1 serves as a control group: Any subsequent experiment where the task manipulation reduces the SPN to approximately zero will likely be significantly different from the large SPN in Experiment 1. If SD = 1.5 μV in both Experiments (a conservative estimate, given previous SPN research), Cohen's d_s would be 1. Our sample 40 per group provides >95% power for finding such a large between-subjects effect with an independent samples t test (alpha = .05, two tailed).

2.6. Bayesian analysis

The familiar *p* value from t tests tells us the probability of finding the observed data given the null hypothesis: p(D|H0). However, a *non*-significant *p* value does *not* confirm the null hypothesis. In other words, a non-significant *p* value should be interpreted as absence of evidence, not evidence of absence. This limitation was particularly pertinent for the current project because we were theoretically interested in finding tasks where the SPN is abolished. We therefore used Bayesian t tests that can confirm the null.

We start by assuming that H0 and H1 are equally likely – Our prior odds in favour of H0 and H1 are 1:1. New evidence can be used to update the prior odds, giving posterior odds. To do this, we compute the ratio of likelihoods, or Bayes factor [p(D|H0): p(D|H1)]. The Bayes factor thus tells us whether to give more credence to null hypothesis (if BF01 > 3), to the alternative hypothesis (if BF01 < 1/3) or whether to remain agnostic (if BF01 is between 1/3 and 3). For Bayesian t tests, we used the conventional Cauchy prior with r-scale of .707.

Rather than running a single Bayesian t test per experiment, ran one for each timepoint along the SPN difference wave (https://klabhub.github.io/bayesFactor/). The resulting 'BF01 wave' allows us to determine whether the brain responses at a given time point differs between two conditions (BF01 < 1/3), is the same in both conditions (BF01 > 3), or whether to remain uncertain (BF01 between 1/3 and 3). In all 8 experiments, BF01 dipped below 1/3 at some interval (see panel C in results figures).

3. Experiment 1: Attend to regularity

Experiment 1 provided our baseline measure of SPN amplitude. How large is the SPN when participants are discriminating regularity in these stimuli? This SPN serves as a point of comparison for further experiments.

3.1. *Experiment 1 Method*

There were 40 participants (Mean age = 20.2, range = 18 to 39, 11 male, 4 left-handed). Participants discriminated whether patterns were 'Symmetrical' or 'Random' using the left (A) and right (L) keys on a standard keyboard. Responses were entered after stimulus offset and there were no requirements to respond quickly. The response mapping was randomized on each trial to prevent lateralized motor preparation. If participants pressed the wrong button, the word 'wrong' appeared in red for 1500 msec. Single channels were interpolated from 4 participant datasets. On average 6.225 ICA components were removed (min 0, max 15). Mean trial inclusion rate was very similar in symmetry and asymmetry conditions (95 *vs* 96%).

3.2. *Experiment 1 Results*

Participants gave the correct answer on most trials (Mean correct = 97.1%, worst participant = 88.1%, best participant = 99.7%). We observed a very robust SPN signal (Fig. 3). Grand average ERP waves from posterior electrodes are shown in Fig. 3A. The symmetry–asymmetry difference wave is shown in Fig. 3B. When the 95% CI ribbon falls below zero, we have a significant SPN. Bayes factor as a function of time is shown in Fig. 3C. Until ~160 msec post stimulus onset, there was either *evidence of absence* (BF01 > 3) or *absence of evidence* (BF01 between 1/3 and 3). Soon after ~170 msec, there was overwhelming evidence that the symmetry and asymmetry waves diverged (BF01 < 1/100). The SPN had the usual bilateral posterior topography (Fig. 3D). A violin plot with descriptive statistics is shown in Fig. 3E. This shows that SPN was present in all 40 participants, and individual participant SPNs were normally distributed across a range from −.326 to −5.217 μV. Mean amplitude during the 250–400 msec interval was −2.423 μV [t (39) = −13.420, p < .001, d_z = −2.122].

4. Experiment 2: Attend to luminance (easy)

Most features of Experiment 2 were identical to Experiment 1. However, regularity was not task relevant in Experiment 2, and participants discriminated dot luminance instead. We expected the SPN to be reduced, but not abolished in Experiment 2.

4.1. *Experiment 2 Method*

Another group of 40 participants were recruited (Mean age = 20.5, range = 18 to 33, 12 male, 8 left-handed). The stimuli were constructed with the same algorithm as Experiment 1. Participants discriminated whether luminance of the dots was 'grey' or 'black' using the left and right keys on the keyboard. The unpredictable response mapping protocol was used again. Single channels were interpolated from 4 datasets, and 2 channels were interpolated from another 2 datasets. On average, 7.15 ICA components were removed (min 1, max 15). Mean trial inclusion rate was very similar in symmetry and asymmetry conditions (94 *vs* 95%).

4.2. *Experiment 2 Results*

Participants gave the correct answer on most trials (Mean correct = 96.6%, worst participant = 85.9%, best participant = 100%). There was again an SPN in Experiment 2 (Fig. 4). Mean SPN amplitude during the 250–400 msec interval was −.835 μV [t (39) = −4.951, p < .001, d_z = −.783]. The SPN was found in 36/40 participants.

After the EEG recording was complete, 26/40 participants claimed to have noticed that the patterns were either symmetrical or asymmetrical, and 2 more gave ambiguous responses. SPN amplitude was similar the group of participants who noticed the regularity manipulation and the group who did not [M = −.868 *vs* −.935 μV, Welch's t (15.514) = −.153, p = .880, d_s = −.057].

5. Experiment 3: Attend to luminance (difficult)

Experiment 3 was our first severe test of SPN automaticity. Experiment 3 was identical to Experiment 2, but the difference between light and dark dots was substantially reduced. The centre of the dark dots was now approximately 3 CD/M^2, and the centre of the light dots was still 4 CD/M^2. Unlike Experiment 2, the luminance discrimination task in Experiment 3 was non-trivial, and performance was far below ceiling (mean correct = 64.4%, worst participant = 52.8%, best participant = 72.8%). Indeed, the best performing participant in Experiment 3 did not reach the level of the worst performing participant in Experiment 2. We reasoned that the difficult luminance discrimination in Experiment 3 might compete with symmetry processing and abolish the SPN.

5.1. *Experiment 3 Method*

Another group of 40 participants was recruited (Mean age = 19.9, range = 18 to 39, 10 male, 8 left-handed). Single channels were interpolated from 11 datasets, 2 were interpolated from another dataset, and 3 from another 2 sets. On average 7.45 ICA components were removed (min 0, max 26). Mean trial inclusion rate was very similar in symmetry and asymmetry conditions (~95%).

5.2. *Experiment 3 Results*

Results are shown in Fig. 5. Mean SPN amplitude during the 250–400 msec interval was −1.410 μV [t (39) = −6.806, p < .001, d_z = −1.076]. Contrary to our predictions, the SPN was significantly larger in Experiment 3 than Experiment 2 [t (78) = 2.151, p = .035, d_s = .481]. After the EEG recording was

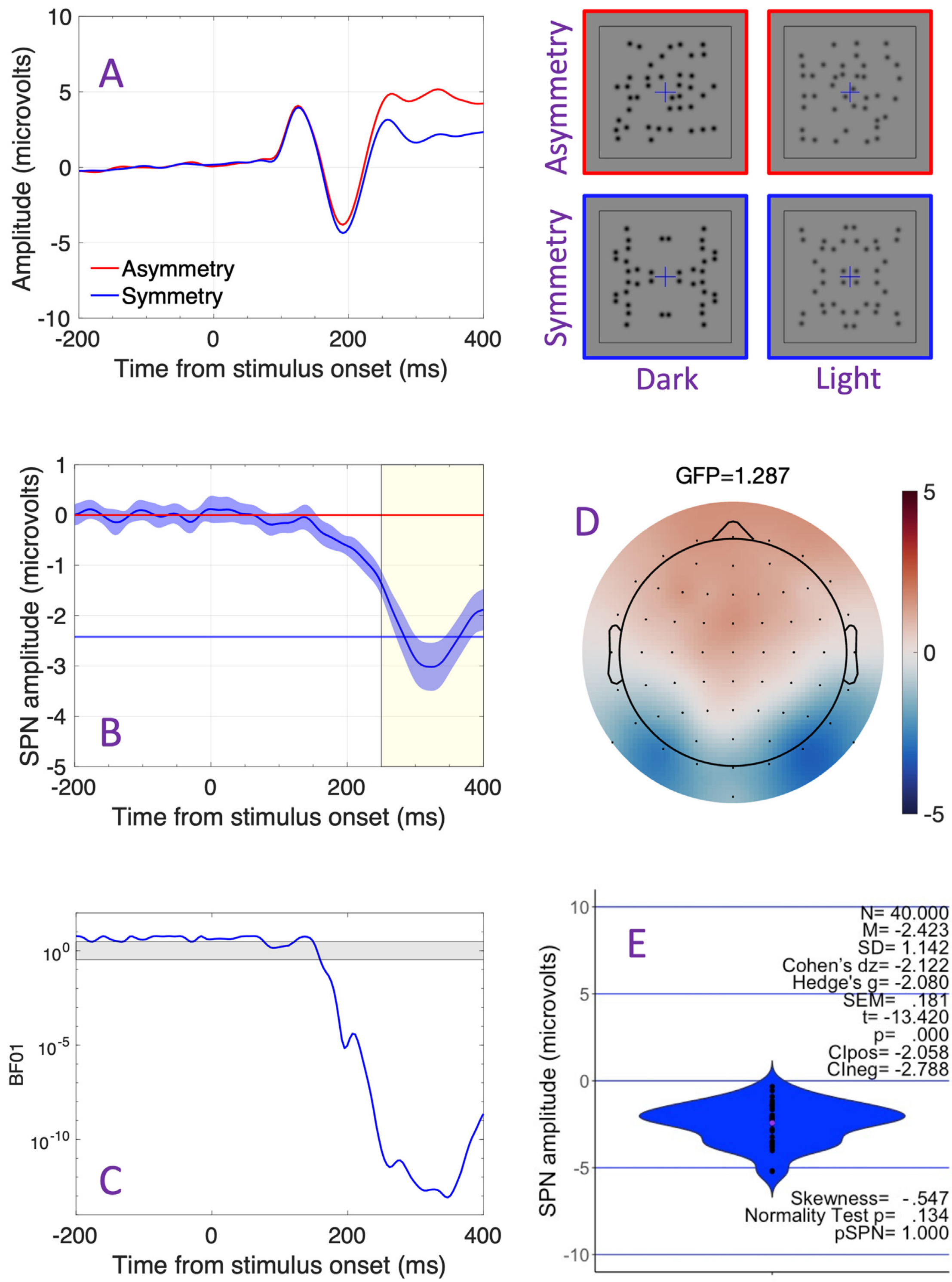

Fig. 3 – Experiment 1 results. Participants judged whether the stimuli were symmetrical or asymmetrical in Experiment 1. A) Grand-average ERP waves from posterior electrode cluster [PO7, O1, O2 and PO8]. B) Difference between symmetry and asymmetry waves with 95% CI ribbon. When the ribbon falls below zero, we have a significant difference between the conditions ($p < .05$, two-tailed). The blue horizontal indicates mean amplitude in the analysed interval (yellow). C) A 'Bayes factor SPN'. To generate this plot, we ran a Bayesian one sample t test on every timepoint along the SPN difference wave. When BF01 is above 3, we can assume the brain response is the same in symmetry and asymmetry conditions. When it is below 1/3, we can assume the brain response is different in symmetry and asymmetry conditions. In Experiment 1, the evidence for a difference became overwhelming at ~170 msec. D) Topographic difference map on activity averaged over the 250–400 msec interval. Here the SPN appears blue at posterior electrodes. The GFP label above the topoplot refers to Global

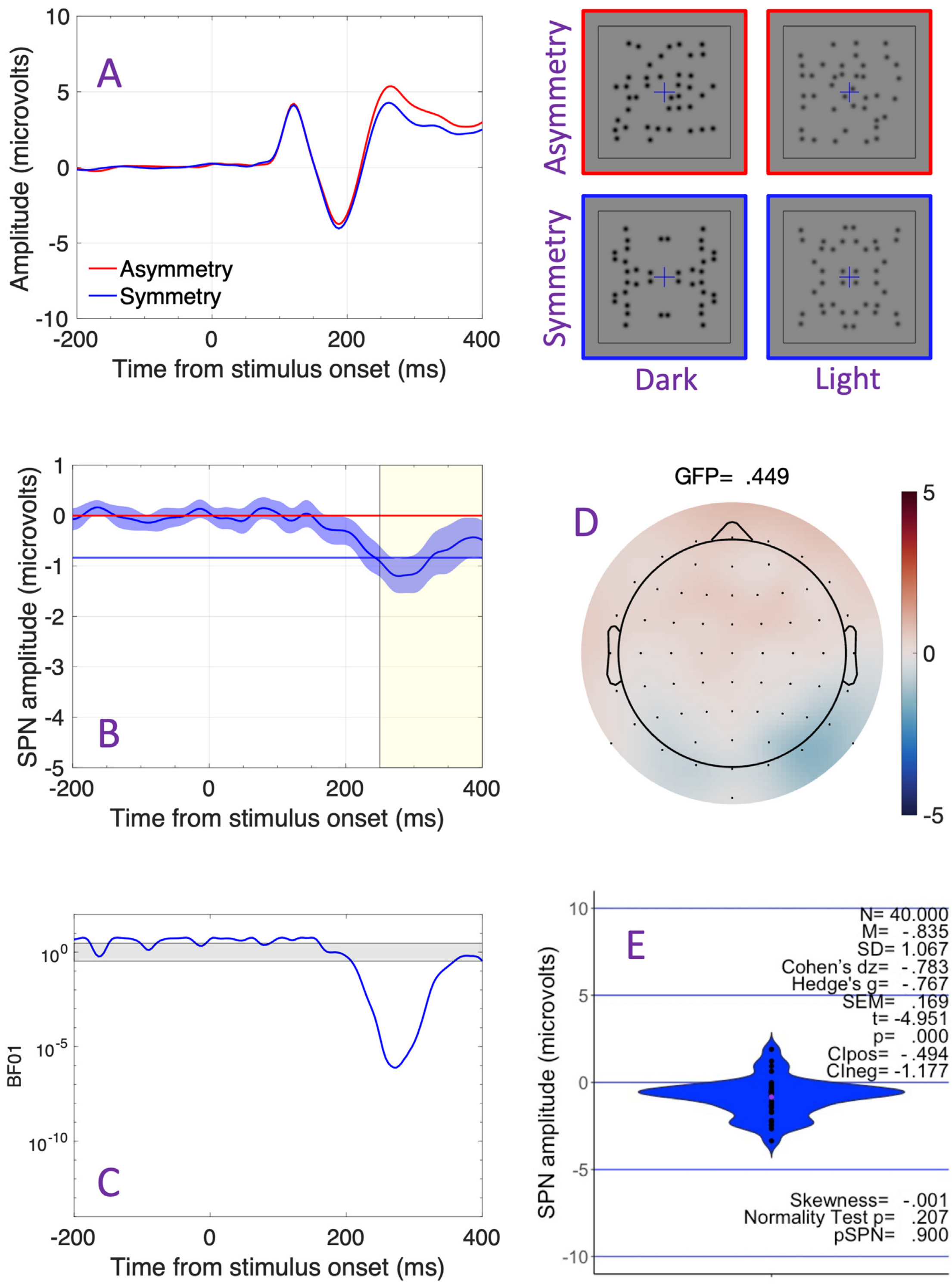

Fig. 4 – Experiment 2 results. Conventions are the same as Fig. 3. Participants judged whether the dots were grey or black in Experiment 2. There was still an SPN response, although symmetry was not task relevant.

Field Power (GFP): This is SD of amplitudes across the 64 electrodes in the symmetry–asymmetry difference map. E) Violin plot showing distribution individual participants SPNs around the grand average. Descriptive and inferential statistics are included as annotations.

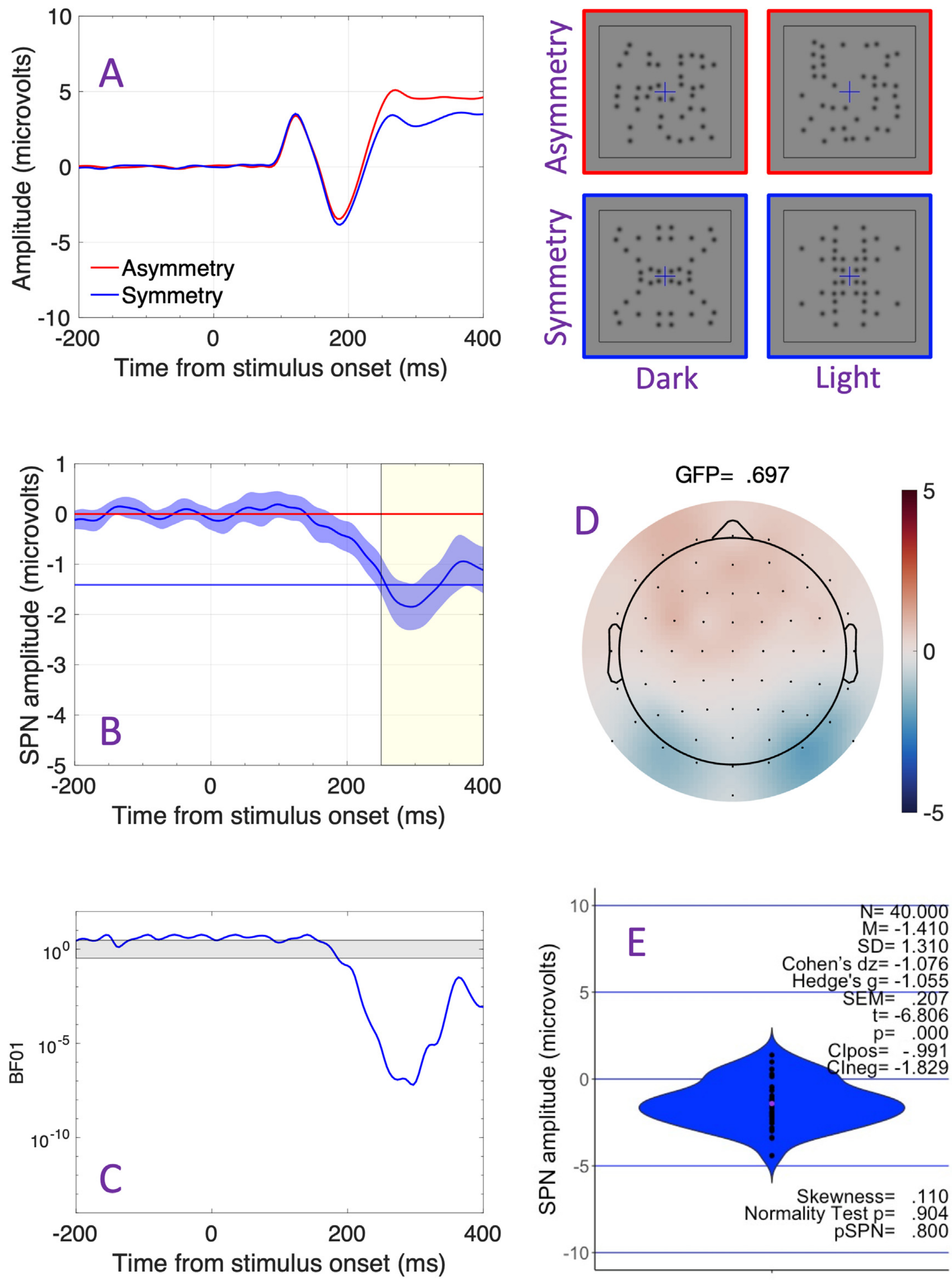

Fig. 5 – Experiment 3 results. Participants judged whether the dots were light or dark in Experiment 3, as they did in Experiment 2, but this difference between luminance levels was reduced. This manipulation did not reduce SPN amplitude.

complete, 25/40 participants claimed to have noticed the regularity manipulation, and one gave an ambiguous response (compared with 26/40 Experiment 2). There was a trend for the group who noticed the regularity manipulation to have larger SPNs [M −1.750 *vs* −.914 μV, Welch's t (22.453) = 1.874, $p = .074$, $d_s = .645$]. Considering the results of Experiment 3, we can confidently say that increasing the difficulty of a luminance task does not inhibit symmetry processing.

6. Experiment 4: Attend to aspect ratio of central cross

There was a very robust SPN when participants actively discriminated regularity (Experiment 1), and this was reduced, but not abolished, when participants discriminated luminance (Experiments 2 and 3). These SPNs are interesting comparisons, but SPNs during luminance and colour discrimination tasks have been observed before (e.g., Makin et al., 2020). Experiment 4 broke new ground in SPN research by building on the influential intentional blindness research of Mack and Rock (1998). The stimuli were the same as Experiments 1–3, but participants judged whether the horizontal or vertical arms of the central fixation cross were longer, while ignoring the regularity and luminance dimensions. Mack and Rock (1998) found that many participants remained unaware of the visual background during such cross aspect ratio discrimination tasks. Experiment 4 can determine whether symmetry is processed under these conditions.

As a precursor to EEG Experiment 4, we ran a behavioural Mack-and-Rock-type inattentional blindness study with the same stimuli. This demonstrated complete inattentional blindness for changes between symmetry and asymmetry when attending to cross aspect ratio.

6.1. *Behavioural inattentional blindness experiment*

Forty participants were involved (aged 18 to 53, 14 male, 3 left-handed). Each participant saw 4 blocks with just 4 trials (Fig. 6). Stimuli were the same as in the subsequent EEG experiment. Each stimulus was presented for 300 msec.

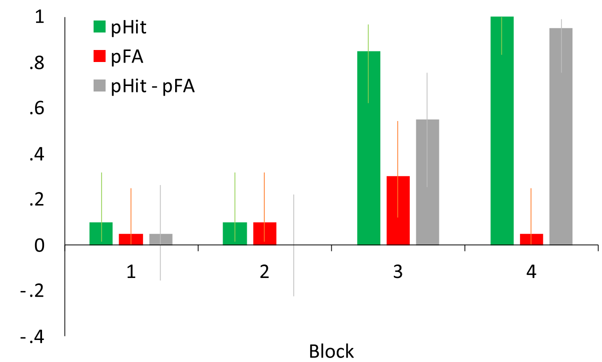

Fig. 7 – Results of the behavioural inattentional blindness experiment. Grey bars above zero indicate sensitivity to changes between background symmetry and asymmetry on the critical trials. Asymmetric error bars = 95% confidence intervals (calculated with the Clopper-Pearson method using DescTools and PropCIs packages in R 4.2.2).

In the first block, participants discriminated the aspect ratio of a superimposed cross. They ignored the background, and judged whether the horizontal or vertical arm of the cross was longer. On the fourth trial the regularity of the background sometimes changed. This is known as the critical trial. For 10 participants the critical trial involved a change from asymmetry to symmetry (as in the example shown in Fig. 6). For 10 participants the critical trial involved the opposite

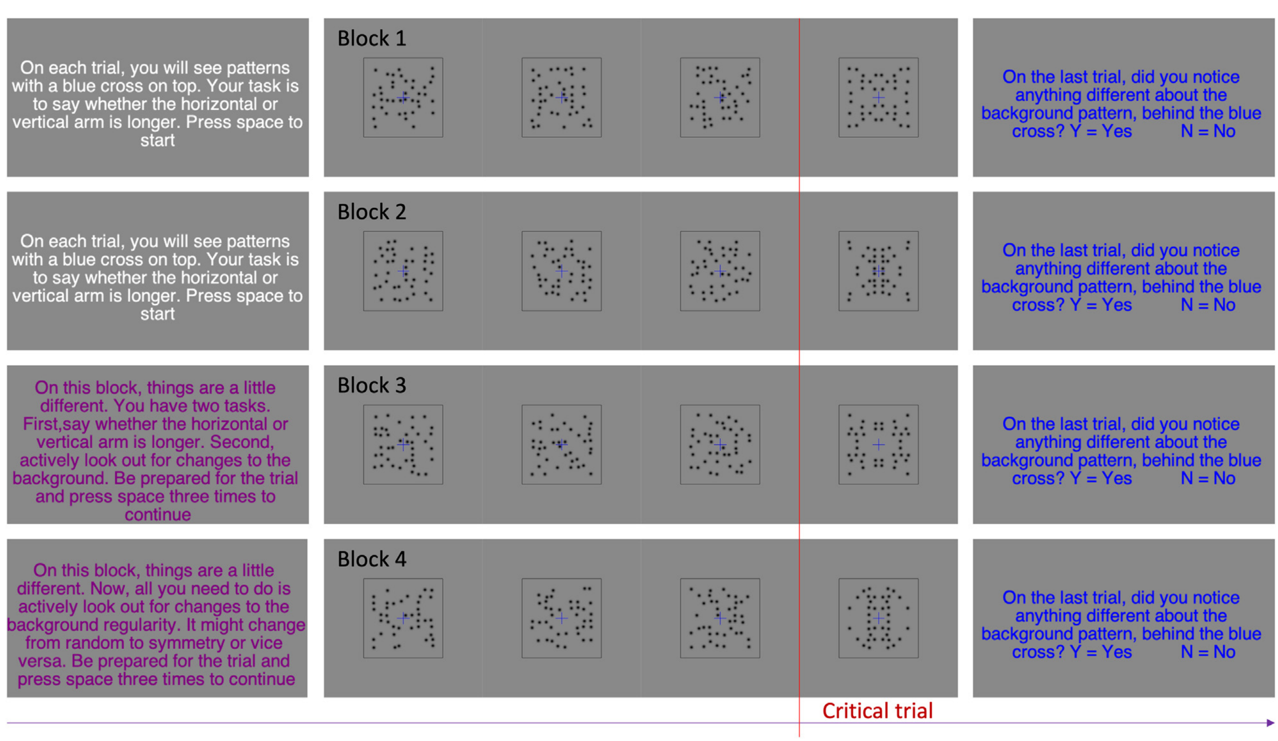

Fig. 6 – Method of the behavioural inattentional blindness experiment. These are examples where the critical trial changed to symmetry following a sequence of 3 asymmetries.

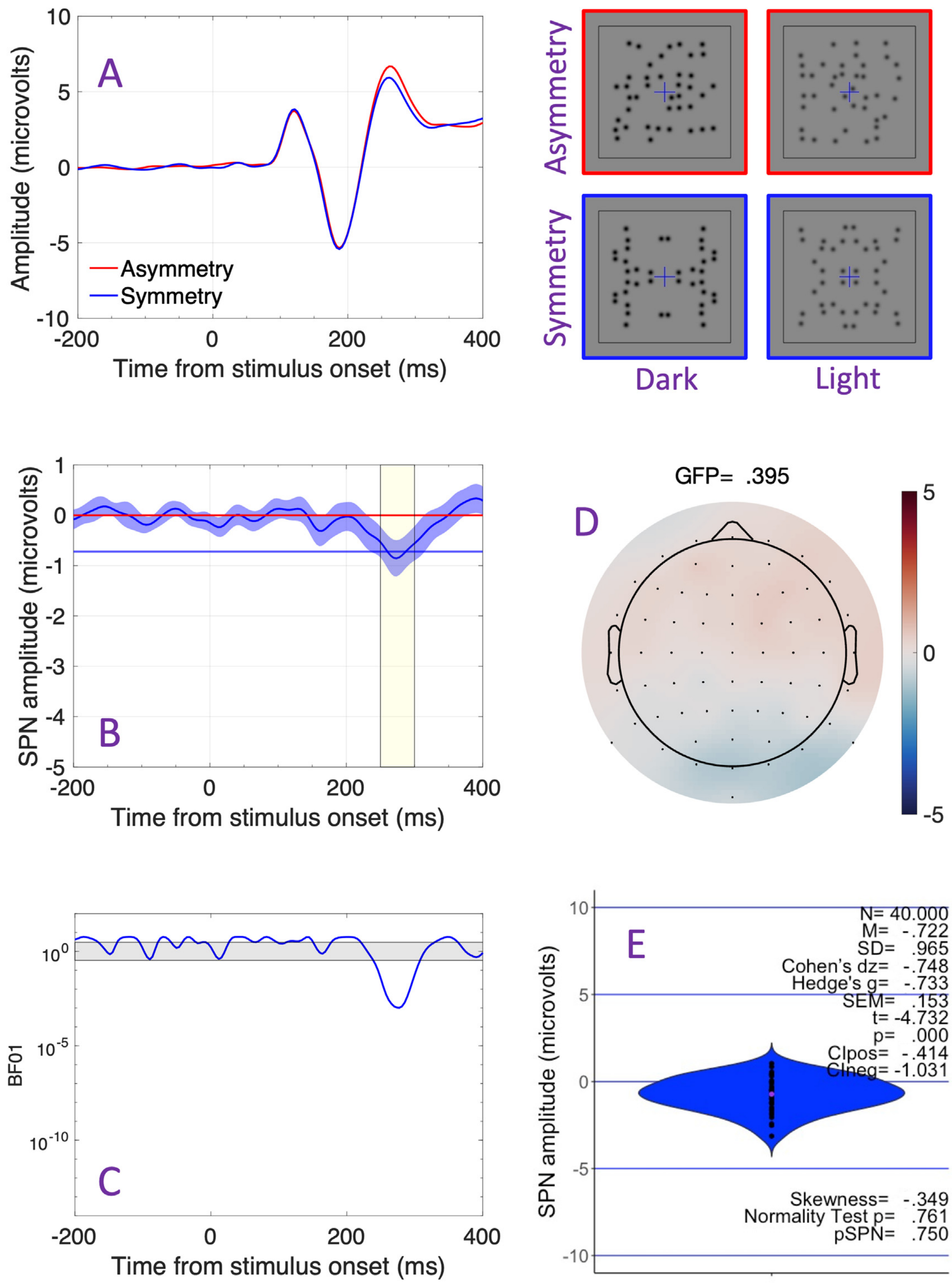

Fig. 8 – Experiment 4 results. Participants discriminated the aspect ratio of the central cross in Experiment 4. The SPN signal was confined to a 250–300 msec sub interval (yellow band in B). The topoplot (D) and violin plot (E) are taken from this sub interval.

change, from symmetry to asymmetry. For 10 participants it involved an asymmetry following asymmetries (no change). For 10 it involved a symmetry following symmetries (no change). After the critical trial, participants were asked whether they noticed anything different. For 20 participants the correct answer was yes. For the other 20 the correct answer was no. If attentional blindness is complete, then the proportion of yes responses would be the same in both groups.

The second block was a repeat of the first. However, participants may have anticipated the change on the critical trial, given their experience with the first block. In the third block the instructions changed again, and we asked participants to look out for changes on the critical trial, as well as performing the cross aspect ratio discrimination task. Finally, on the fourth block, we did everything possible to help participants detect the potential change between symmetry and asymmetry on the critical trial. Here there was no requirement to attend to the aspect ratio of the cross, and only the changing background was relevant (instructions are shown in Fig. 6).

For the 20 participants in the change group, the correct answer was 'yes'. For the other 20 participants in the no change group, the correct answer was 'no'. We calculated the proportion of participants who gave 'yes' responses in the change group (pHits, green bars in Fig. 7) and no change group (pFalseAlarm, abbreviated to pFA, red bars in Fig. 7). The DV was pHit minus pFA (grey bars in Fig. 7). This controls for response bias. If all observers were ideal, pHit-pFA would be one. Conversely, if all were completely insensitive to symmetry/asymmetry changes, pHit-pFA would be zero.

In block 1, there was no sensitivity to changing background regularity on the critical trials (pHit-pFA = .05, χ^2 (1) = .360, p = .548, Cramer's V = 0). In block 2, participants may have anticipated the changing background on the critical trial given their recent experience, but pHit-pFA was 0 [χ^2 (1) = 0, p = 1, Cramer's V = 0]. In block 3, participants were instructed to look out for a changing background as well as completing the usual cross aspect ratio task. In block 3 pHit-pFA increased to .55 [χ^2 (1) = 12.768, p < .001, Cramer's V = .506]. Finally, in block 4, where participants only had to look out for a changing background, pHit-pFA increased to .95 [χ^2 (1) = 36.190, p < .001, Cramer's V = .901].

Across all blocks, participants performed better than chance on the cross aspect ratio task [Mean p correct = .56, t (39) = 2.628, p = .012, d_z = .414].

This behavioural experiment shows that novel changes from symmetry to asymmetry and vice versa can be easily discriminated when people are actively looking for them, but they are not usually noticed spontaneously. According to the rationale of Mack and Rock (1998), this demonstrates inattentional blindness for background symmetry. However, background symmetry may be processed unconsciously in the extrastriate cortex. This was examined with EEG in Experiment 4.

6.2. *Experiment 4 Method*

Another group of 40 participants were involved in the EEG experiment (Mean age = 21.1, range = 18 to 45, 11 male, 7 left-handed). EEG analysis was the same as Experiments 1–3. A single channel was interpolated from 1 participant. On average 6.625 ICA components were removed (min = 1, max = 23). Mean trial inclusion rate was very similar in symmetry and asymmetry conditions (~97%).

6.3. *Experiment 4 Results*

As with the behavioural experiment, participants were all above chance in the cross aspect ratio discrimination task (Mean correct = 82.1%, worst participant = 65.9%, best participant = 97.1%). SPN results are shown in Fig. 8. The SPN was present, but only in a sub interval from 250 to 300 msec. The SPN was not significant in the pre-registered 250–400 msec interval [M = −.249 μV, t (39) = −1.953, p = .058, d_z = −.309, two-tailed]. Post hoc analysis of sub windows (with correction for multiple comparison) revealed a significant SPN between 250 and 300 msec [M = −.772 μV, t (39) = −4.732, p < .001, d_z = −.748], but not between 300 and 400 msec [M = −.013 μV, t (39) = −.102, p = 1, d_z = −.016]. BF01 dipped far below 1/3 (Fig. 9C) and the SPN was present in 30/40 participants during the 250–300 msec interval (p = .002, binomial test, Fig. 8E).

This analysis is limited by the post hoc interval. However, it would be misleading to conclude that there was no SPN in Experiment 4 – after all, there was a short sub interval with a robust posterior negativity. This short-lived symmetry response may often be missed by other cognitive systems and fail to enter awareness. Indeed, after the EEG recording was complete, only 12/40 participants consciously noticed the regularity manipulation (and five more gave ambiguous responses). Moreover, the SPN was significantly larger in the minority subgroup who noticed the regularity manipulation [M = −1.093 *vs* −.349 μV, Welch's t (25.61) = 2.842, p = .009, d_s = .988].

7. Experiment 5: Attend to aspect ratio of central cross (symmetry rare)

Experiment 4 indicated some sensitivity to background symmetry during a cross aspect ratio discrimination task that induces inattentional blindness. However, in Experiment 4 there were 160 symmetrical trials, and 160 asymmetrical trials. It might be that if symmetry trials were less frequent, the SPN would be abolished. This possibility was tested in Experiment 5. Experiment 5 was identical to Experiment 4, except that we added another 320 asymmetrical trials. Therefore, symmetry was only present on 25% of the trials, and the experiment was twice as long. Experiment 5 also allowed us to replicate the results of Experiment 4 with an a priori time interval.

7.1. *Experiment 5 Method*

Another group of 40 participants were involved (Mean age = 27.3, range = 18 to 60, 17 male, 7 left-handed). EEG analysis was the same as Experiments 1–4. As with Experiment 4, 160 symmetrical and 160 asymmetrical trials were analysed (leaving 320 spare asymmetrical trials). This made the results of Experiments 4 and 5 directly comparable. Single electrodes were interpolated from 16 participants, and 2 electrodes were interpolated in another participant. On average, 7.1 ICA components were removed (min = 1, max = 19). Trial inclusion rate was very similar in symmetry and asymmetry conditions (~96%).

7.2. *Experiment 5 Results*

Performance on the cross aspect ratio discrimination task comparable to Experiment 4 (Mean correct = 80.7%, worst participant = 49.5%, best participant = 94.1%). SPN results are

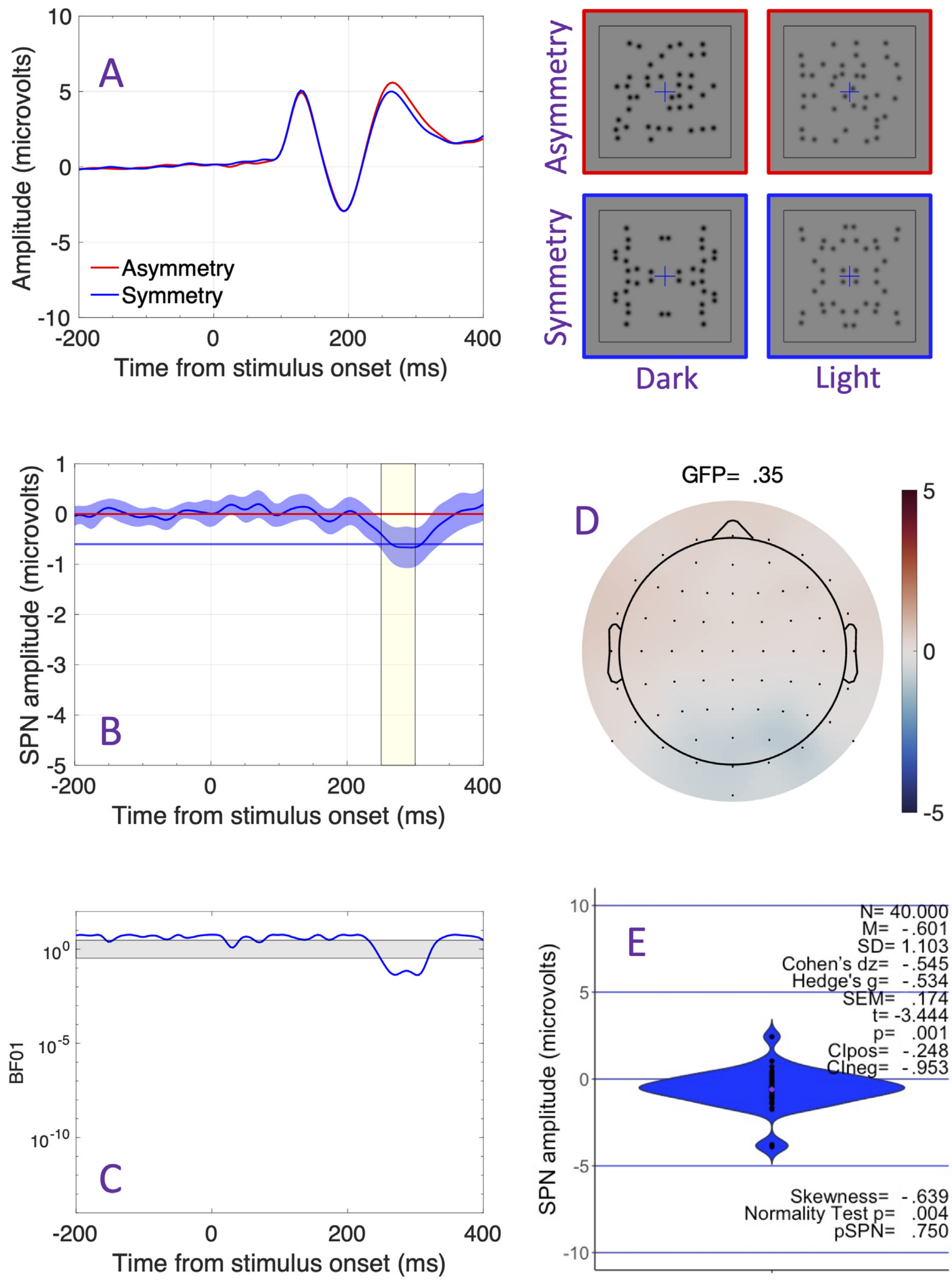

Fig. 9 – Experiment 5 results. Participants again discriminated the aspect ratio of the central cross in Experiment 5. As with Experiment 4, the SPN signal was confined to a 250–300 msec sub interval (yellow band in B). The topoplot (D) and violin plot (E) are taken from this sub interval.

shown in Fig. 9. As in Experiment 4, the SPN was present, but only in a sub interval from 250 to 300 msec [M = −.601 μV, t (39) = −3.444, p = .001, d_z = −.545]. Again, BF01 dipped far below 1/3 during this interval (Fig. 9C). Although the individual participant SPNs were not normally distributed during this interval, the SPN was present in 30/40 participants (p = .002, binomial test, Fig. 9E). Only 6/40 participants noticed the regularity manipulation. The SPN was larger, but not significantly so, in this small subgroup [M = −.936 *vs* −.541 μV, Welch's t (16.162) = 1.356, p = .194, d_s = .436].

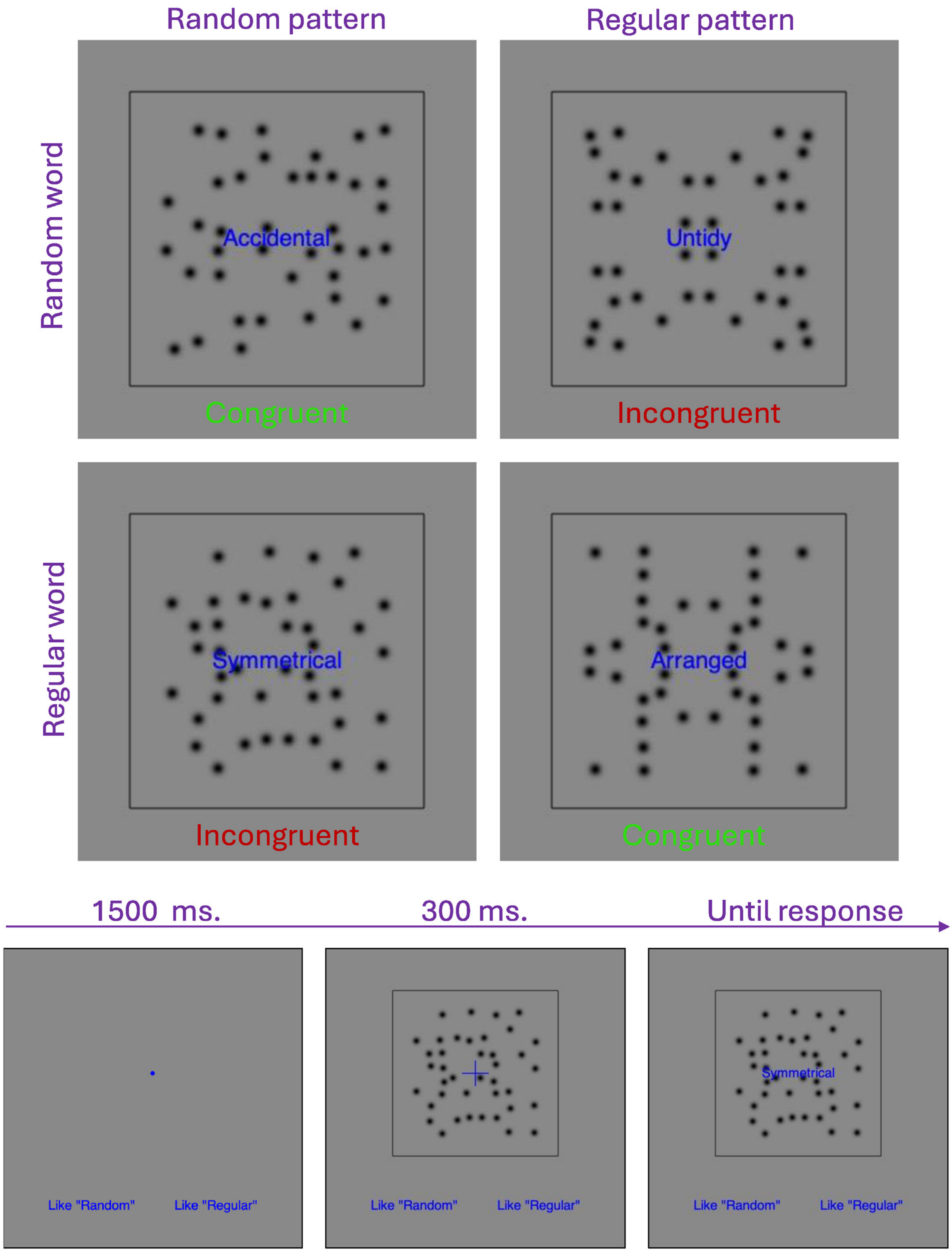

Fig. 10 – Experiment 6 method. The left panel shows nature of congruent and incongruent trials. The right panel shows duration of each interval within a trial.

8. Experiment 6: Attend to the semantic regularity of superimposed words

In Experiments 2–5, participants could ignore the regularity of the background pattern. These task manipulations reduced the SPN but did not abolish it. In Experiment 6 we developed a new task where participants may actively inhibit the background (Fig. 10). After the pattern was presented for 300 msec, a central word appeared. The central word was semantically like the word 'regular' (e.g., order) or semantically like the word 'random' (e.g., chaotic). The task was to classify the central word as quickly and accurately as possible. This yielded congruent trials (regular background and regular word, or random background and random word) and incongruent trials (regular background and random word, or random background and regular word). In a small pilot study, we found no interference effects: Median response times on the word classification tasks were similar on the congruent and incongruent trials. This suggests participants had inhibited the distracting background pattern so they could classify the word. In Experiment 6 we ran the same task while recording EEG. We reasoned that inhibition of the background might abolish the SPN.

8.1. *Experiment 6 Method*

Forty participants were involved (mean age = 19.5, range 18–26, 9 male, 4 left-handed). The stimuli were the same as Experiments 1–5. After a 1500 msec baseline, patterns were presented alone for 300 msec. Unlike previous experiments, the pattern then remained on screen with a superimposed word until a response was entered. Participants were required to classify the words as 'Like Regular' or 'Like Random' as quickly and accurately as possible.

Superimposed words semantically related to random were *Asymmetrical, Chaotic, Noisy, Unarranged, Messy, Misaligned, Accidental and Untidy*. Superimposed words semantically related to regular were *Symmetrical, Systematic, Structured, Arranged, Order, Aligned, Deliberate, and Tidy*. The words were chosen to have the same average number of characters, and this occupy approximately the same average area. Words could overlap with the central dots. On each trial, a word from the appropriate category was selected at random.

Response mapping did not change between trials, because this would slow responses and reduce the precision of RT measurement. Instead, we balanced response mapping across participants. For half the participants, the left key was used for 'Like Regular', and the right key was used for 'Like Random'. For the other half, response mapping was reversed.

Single channels were interpolated in 2 datasets. On average 7.925 ICA components were removed (min 1, max 22). Mean trial inclusion rate was very similar in symmetry and asymmetry conditions (~94%).

8.2. *Experiment 6 Results*

Participants classified the words correctly on most trials and error rate was similar on congruent and incongruent trials (3 *vs* 4%, $p = .14$). However, unlike the pilot study, median RT was significantly faster on congruent trials than the incongruent trials [743 *vs* 759 msec, $t\ (39) = 3.422$, $p = .001$, $d_z = .541$]. Furthermore, 31/40 participants consciously noticed the fact that patterns were either symmetrical or asymmetrical, 8 others gave ambiguous answers and 1 gave no answer.

As shown in Fig. 11, there was a robust SPN in Experiment 6 [$M = -1.358\ \mu V$, $t\ (39) = -7.620$, $p < .001$, $d_z = -1.205$]. The 40 individual participant SPNs were not normally distributed. However, the SPN was present in 37/40 participants ($p < .001$, binomial test). There was no correlation between SPN amplitude and the magnitude of the behavioural congruence effect ($r = -.011$, $p = .944$).

We conclude that this task does not block symmetry processing in the extrastriate cortex and does not prevent visual representations from interfering with word classification. In other words, the extrastriate symmetry response was not successfully quarantined from other cognitive operations.

9. Experiment 7: Attend to meaning of negative superimposed words

Over a decade ago, Rampone et al. (2014) conducted an experiment with symmetrical or asymmetrical square patterns. Positive or negative words were overlayed in the centre. When the words were positive, there was a clear SPN. When the words were negative, there was no SPN (data point indicated with arrow in Fig. 1B).

We revisited this apparent anomaly in Experiment 7. We tested whether attention to negative words does indeed block symmetry processing, as the results of Rampone et al. (2014) suggest. The same patterns were presented with a small negative word in the centre. The participant's task was to classify the word as more like "violence" or more like "disease". Unlike Rampone et al. (2014), we did not include a positive word condition. We increased sample size to 52 in Experiment 7. This gave 80% statistical power for finding small SPNs ($d_z = .4$), but also more power for confirming the absence of an SPN with Bayesian t tests.

9.1. *Experiment 7 Method*

Symmetrical and asymmetrical dot patterns were the same as previous experiments. The participant's task was to discriminate between negative words related to violence and negative words related to disease. Negative words were chosen from the Affective Norms for English Words (ANEW) database (Bradley & Lang, 1999). We chose 20 'disease' words and 20 'violence' words. The 20 disease words were *cancer, infection, syphilis, rabies, ulcer, sick, paralysis, poison, toothache, headache, accident, vomit, leprosy, sickness, gangrene, lice, malaria, ache, ambulance, and smallpox*. The 20 violence words were *murderer, suffocate, torture, slaughter, terrorist, abuse, mutilate, killer, hurt, assault, war, bomb, victim, hostage, crucify, massacre, violent, execution, rage, and guillotine*. The disease and violence words were matched in terms of valence (2.057 *vs* 2.002 on a 1–9 scale) and length (6.9 *vs* 6.8 letters). However, the violence words had higher arousal scores (6.735 *vs* 5.599 *vs* on a 1–9 scale). We take this to be a fundamental semantic difference

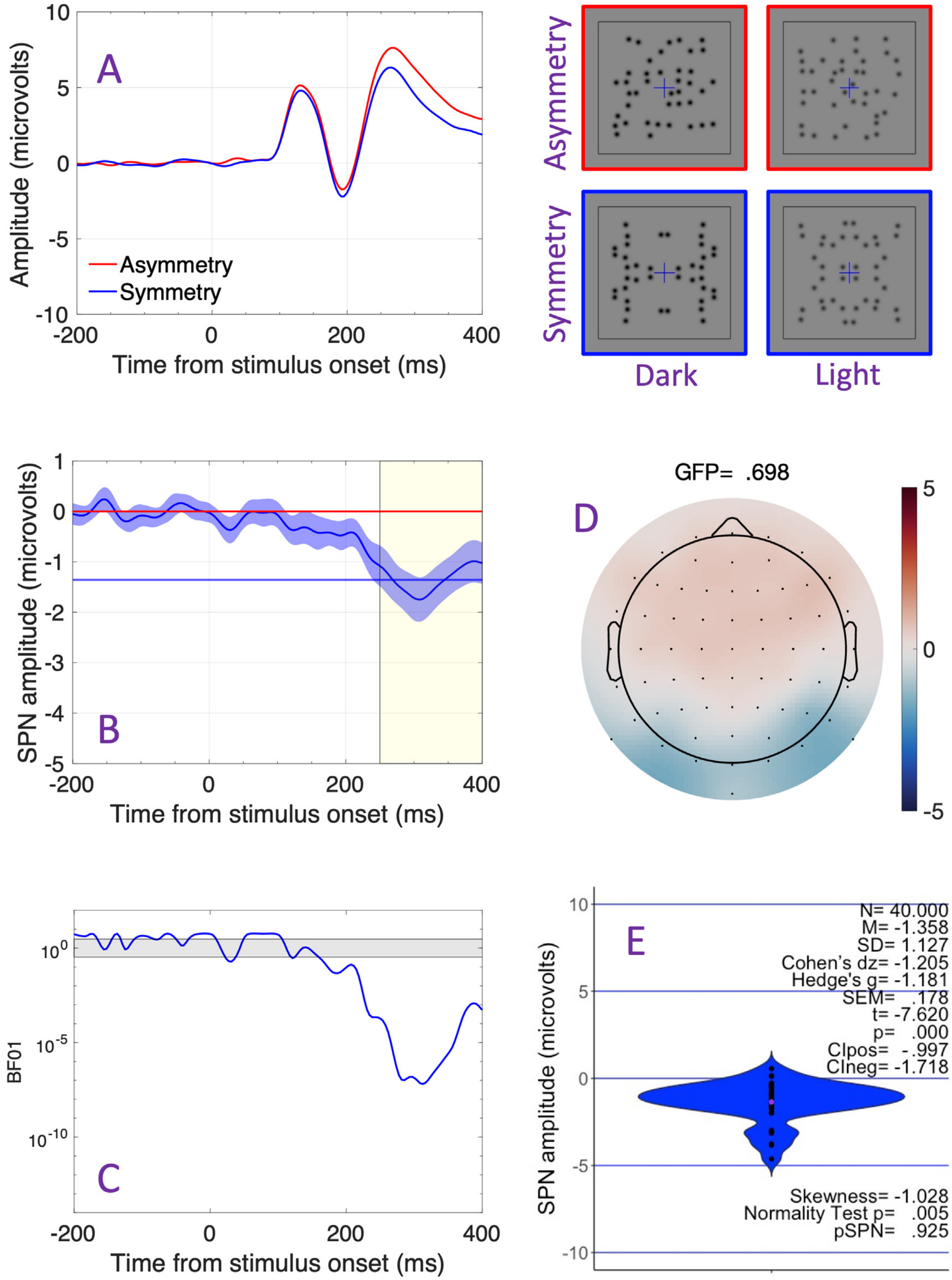

Fig. 11 — Experiment 6 results. In Experiment 6, participants judged whether a central word presented in subsequent interval was semantically like the word 'regular' (e.g., order) or semantically like the word 'random' (e.g., chaotic). Although the background patterns could interfere with the primary word classification task, there was still an SPN signal. In these ERP plots, zero represents the onset of the background pattern, not the onset of the word.

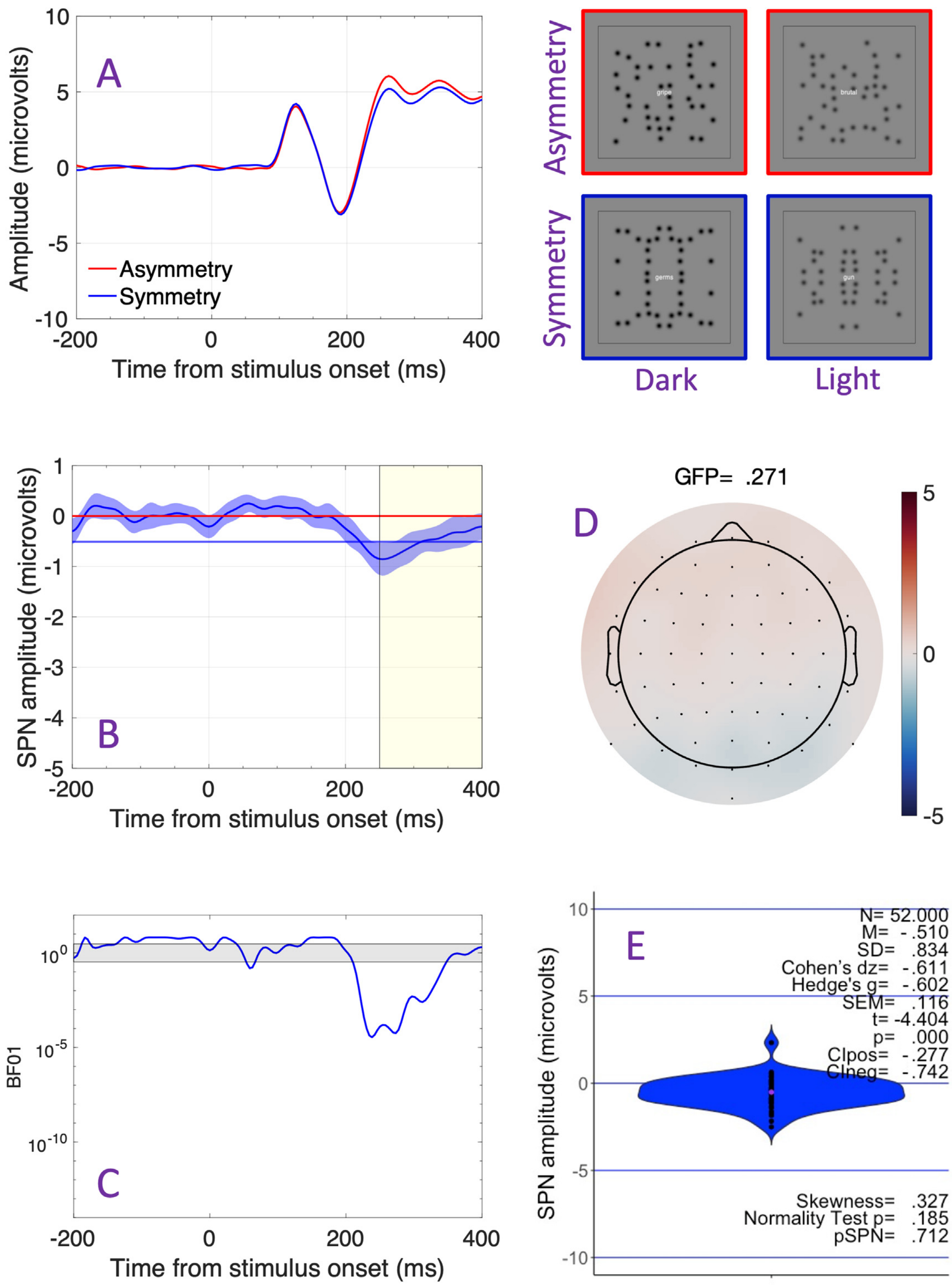

Fig. 12 – Experiment 7 results. In Experiment 7 participants judged whether the central word was related to disease or violence. There was still a substantial SPN signal, although participants were attending to negative words.

between the categories rather than a problematic confound: Violence is more emotionally arousing than disease.

As with previous experiments, there were 320 trials in total, 160 were symmetrical, 160 were asymmetrical. Half the trials involved a disease word, half involved a violence word. Response mapping changed unpredictably between trials. The 40 words were each repeated 8 times in the experiment. Words and patterns were presented simultaneously for 300 msec following a 1500 msec baseline. Font size was small, so the words only occupied around 1 horizontal degree, and never fully occluded a dot element.

Single electrodes were interpolated in 10 datasets, 2 electrodes were interpolated in 4 participant datasets, 3 were interpolated in 3 datasets, and 5 were interpolated in another dataset. On average 7.79 ICA components were removed (min 1, max 29). Mean trial inclusion rate was very similar in symmetry and asymmetry conditions (~97%).

9.2. *Experiment 7 Results*

On average, participants correctly classified 93% of disease words, and 96% of violence words (worst performing participant 80% for disease and 86% for violence, best participant 98% for disease and 100% for violence).

ERP results are shown in Fig. 12. The SPN was significant during the 250–400 msec interval [$M = -.510\ \mu V$, $t\ (51) = -4.404$, $p < .001$, $d_z = -.611$]. Of the 52 participants, 20 consciously noticed the fact that patterns were either symmetrical or asymmetrical (38.4%). The SPN was significantly larger in this subgroup who noticed the regularity manipulation [M $-.811$ *vs* $-.321\ \mu V$, Welch's $t\ (43.666) = 2.179$, $p = .035$, $d_s = .614$].

10. Experiment 8: Attend to orientation of a central diagonal line

So far, no experiments have completely blocked symmetry processing and reduced SPN amplitude to zero. In Experiment 8, we tried a different manipulation inspired by established filter and bootstrapping models of visual symmetry processing.

Filter models begin with the understanding that the striate cortex is like an array of spatial frequency and orientation tuned filters (Mancini et al., 2005; Poirier & Wilson, 2010; Rainville & Kingdom, 2000). *Outputs* from these filters are *inputs* for symmetry detection mechanisms in the extrastriate cortex. One filter model proposes that symmetry detection involves finding midpoint colinear blobs centred on the global axis (Dakin & Watt, 1994).

The *bootstrapping model* (Bellagarda et al., 2023; Wagemans et al., 1993) does not consider image filtering, but proposes that symmetry detection involves discovery of virtual quadrangles connecting the symmetry lines. Once one quadrangle is found, it provides a direction of search for the next quadrangle along the global axis. The bootstrapping operation is thought to happen rapidly and unconsciously. It does not involve deliberate visual comparisons or shifts of spatial attention.

Both filter and bootstrapping models imply, at least indirectly, that symmetry detection would be impaired if representations of global axis orientation were inhibited.

On each trial in Experiment 8, a short blue line was present at the centre of the pattern. Participants discriminated whether the line was closer to horizontal (<45°) or vertical (>45°). We reasoned that the horizontal and vertical axes of the background symmetry might be inhibited by attention to the diagonal line. After all, orientation channels are subject to lateral inhibition, resulting in tilt aftereffects and related phenomena (van der Zwan et al., 1998).

10.1. *Experiment 8 Method*

Another group of 52 participants were involved (mean age = 19.0, range = 18–27, 6 males, 6 left-handed). On half of the trials line orientation was nearer horizontal, on half if was nearer vertical. Line orientation was fully crossed with other factors. When line orientation was nearer horizontal, orientation was random set at ±38, 39, 40, 41 or 42°. When orientation was nearer vertical, orientation was randomly set at 48, 49, 50, 51 or 52°. The use of 5 orientation levels within each category prevented over familiarity with just two orientations.

Single channels were interpolated in 8 datasets, 2 were interpolated in 4 datasets, 3 were interpolated in 1 dataset, and 5 were interpolated in another dataset. On average 5.58 ICA components were removed (min 1, max 14). As with experiments 1–7, mean trial inclusion rate was very similar in symmetry and asymmetry conditions (~97%).

10.2. *Experiment 8 Results*

Orientation discrimination was above floor but below ceiling (Mean correct = 86.8%, worst participant = 49.7, best participant = 95.3%). ERP results are shown in Fig. 13. The SPN was significant in the a priori 250–400 msec interval [$M = -.366\ \mu V$, $t\ (51) = -3.183$, $p = .002$, $d_z = -.441$]. However, it was strongest in a 200–300 msec interval [$M = -.589\ \mu V$, $t\ (51)\ -5.533$, $p < .001$, $d_z = -.767$]. Of the 52 participants, just 7 consciously noticed the regularity manipulation (13%). The SPN was not significantly different in this group [$M = -.355$ *vs* $M = -.626$, μV, Welch's $t\ (7.115) = -.707$, $p = .502$, $d_s = -.314$].

11. Combined analysis

A summary of all results is shown in Fig. 14A. There was a large neural response to symmetry when participants attended to regularity in Experiment 1, and this was reduced, but not abolished, when participants attend to other features in Experiments 2–8. There was a main effect of Experiment on SPN amplitude in Univariate ANOVA [$F\ (7{,}336) = 16.550$, $p < .001$ $\eta^2 = .256$].

This main effect requires clarification. Are the SPN differences primarily driven by task effects on symmetrical trials or asymmetrical trials? Computing the SPN as a difference wave does allow us to distinguish these possibilities. We thus analysed amplitude in symmetry and asymmetry condition separately (Fig. 14). The effect of Experiment was stronger in the symmetry condition [$F\ (7{,}336) = 2.212$, $p = .033$, $\eta^2 = .044$] than the asymmetry condition [$F\ (7{,}336) = .784$, $p = .601$, $\eta^2 = .016$]. We conclude that attending to regularity enhances the subjective symmetry of symmetrical stimuli more than it enhances the asymmetry of asymmetrical stimuli.

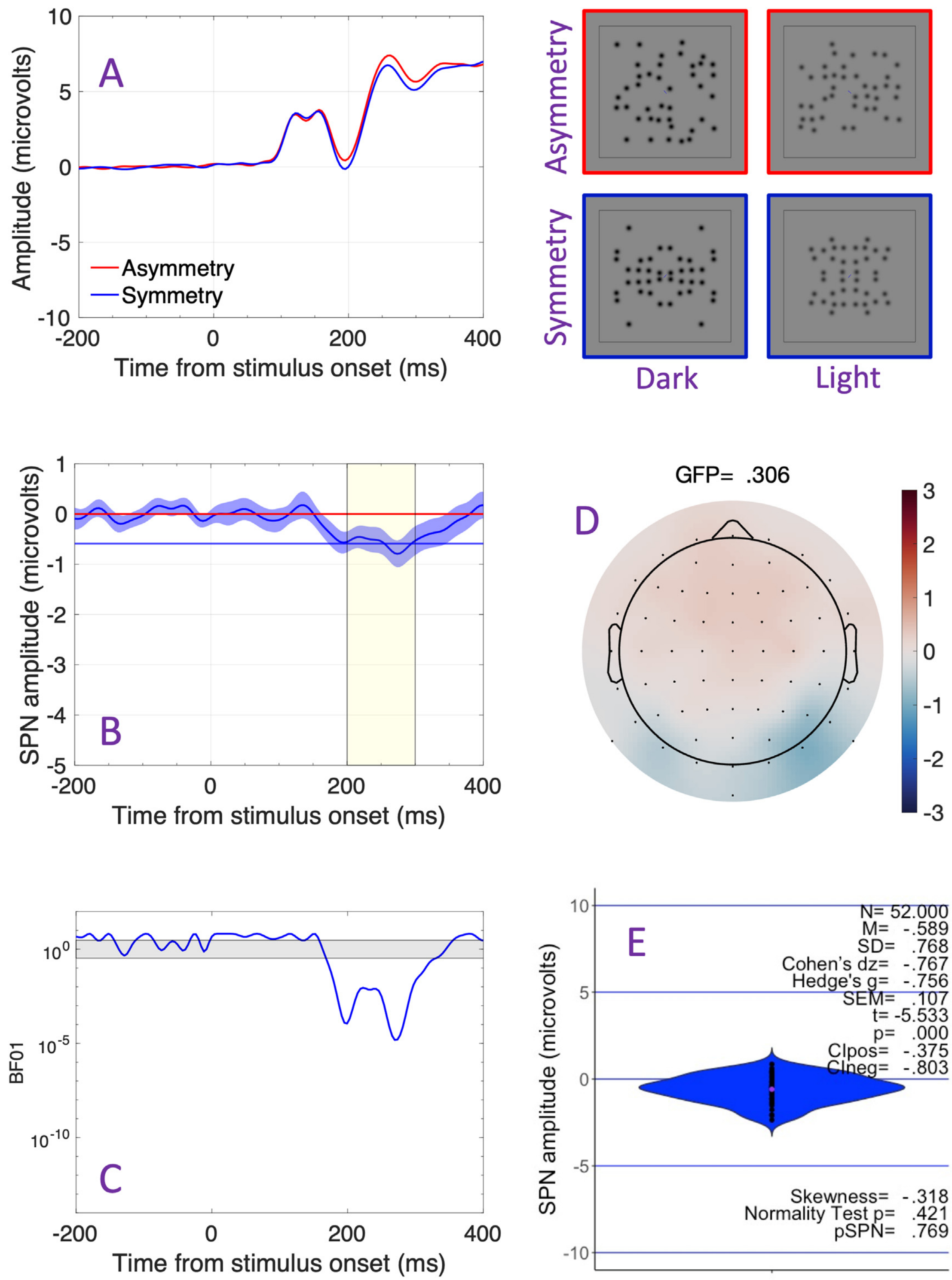

Fig. 13 – Experiment 8 results. In Experiment 8 participants judged whether a short diagonal line was nearer horizontal or vertical. The SPN was still present, but strongest in a 200–300 msec interval (highlighted yellow in B). This interval was used in topoplot (D) and violin plot (E).

The SPN was often enhanced in participants who noticed the regularity manipulation compared those who did not (reaching significance in Experiment 4 and 7). Regression analysis confirmed the importance of subjective awareness. The categorical predictor Experiment explained 25.6% variance in SPN amplitude. Addition of another categorical predictor, which could be termed ‘Noticed background regularity’ (yes, no) increased this to 29.2% [F change (1,319) = 7.554, $p = .006$].

Fig. 14B shows results computed from participants who noticed the background regularity only (and thus there are far

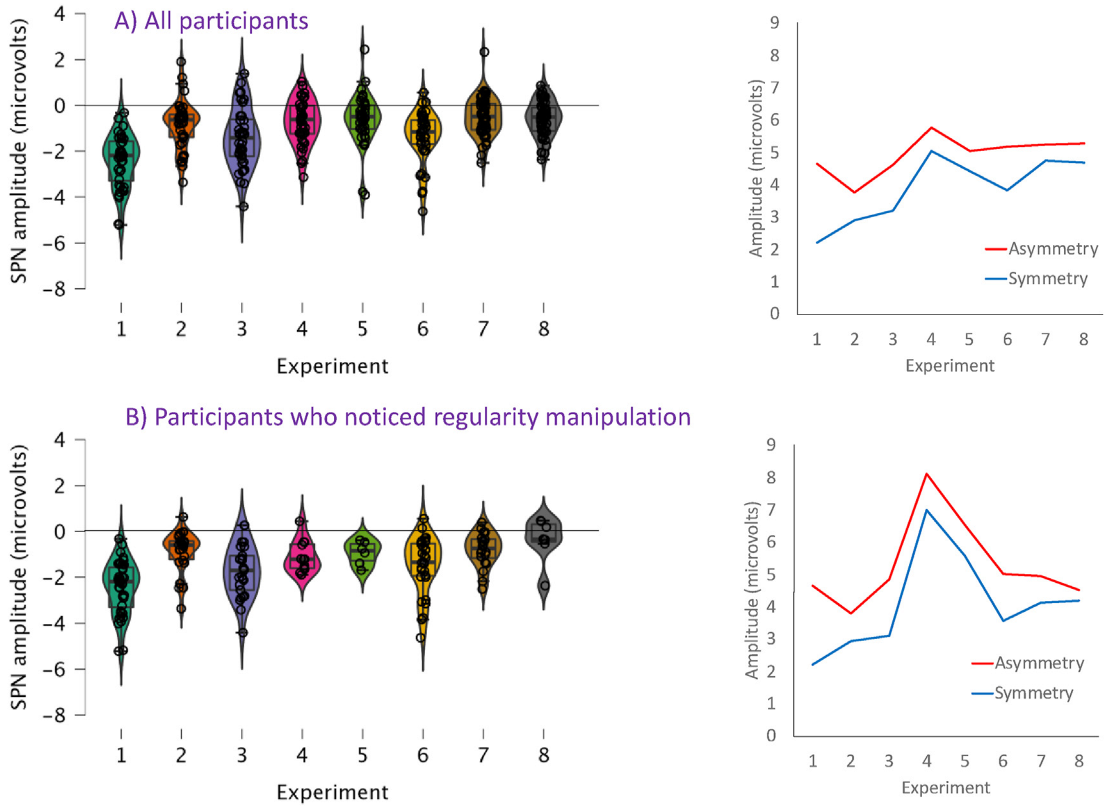

Fig. 14 – Results of all Experiments. A) Results from all participants. The left panel shows a violin plot indicating the distribution of SPN amplitudes in each experiment. The right panel shows mean amplitude of symmetry and asymmetry conditions as separate lines. B) Same results from a subset of participants who noticed the regularity manipulation.

fewer data points under some violins). This is like the original violin plot with all participants in Fig. 14A. Evidently noticing the background regularity was not equivalent to engaging in an active regularity discrimination task.

11.1. *Bayesian pairwise comparisons between experiments*

We used Bayesian independent samples t tests to compare pairs of experiments. This has some advantages over standard frequentist contrasts because it allows us to confirm the absence of pairwise differences, as well as the presence of pairwise differences. Bayes factors from all pairwise comparisons are shown in Table 1. This shows BF10, so >3 indicates evidence for H1, and <1/3 indicates evidence for H0. H1 is that SPN amplitude differs between experiments, H0 is that it does not. The SPN from Experiment 1 was larger than all others (top row). It is also noteworthy that Experiments 4 and 5 give demonstrably similar SPNs (BF10 = .262), even though the frequency of symmetry trials was halved in Experiment 5.

11.2. *Intertrial amplitude distribution*

Before interpreting these results, we needed to consider the distribution of amplitude across trials (for each electrode, timepoint, condition and participant). In Experiments 2–8, the

Table 1 – BF10 from pairwise comparisons between Experiments. Cells are colour coded by conventions for overwhelming, strong, moderate and no evidence for H1 and H0. H1 is that SPN amplitude differs between experiments, H0 is that it does not. Green cells indicate difference between experiments, grey indicates uncertainty, and pink indicates no difference.

	2	3	4	5	6	7	8
1	>1000	63.796	>1000	>1000	302.478	>1000	>1000
2		1.685	.259	.349	1.618	.719	.455
3			4.805	10.008	.236	183.417	83.539
4				.262	5.200	.387	.280
5					11.244	.241	.221
6						283.576	122.722
7							.232

Overwhelming evidence for H1
Strong evidence for H1
Moderate evidence for H1
No evidence
Moderate evidence for H0

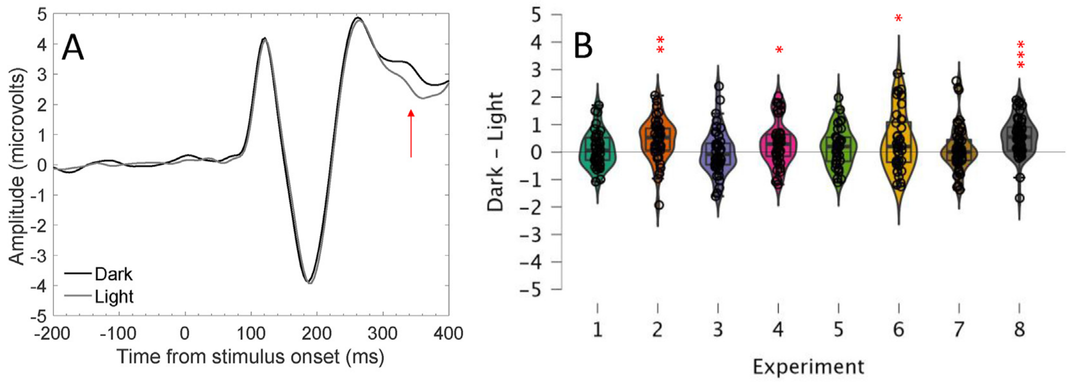

Fig. 15 – ERP responses to dark and light stimuli. A) Grand average ERP waves from Experiment 2, where participants discriminated stimuli by luminance. There is a different brain response around 300–400 msec at posterior cluster (indicated with red arrow). B) Violin plot indicating that Dark-Light difference was significant in Experiments 2, 4, 6 and 8. *p < .05, **p < .01, ***p < .001.

observed SPNs could be driven by a minority of trials where participants spontaneously attended to regularity. However, we think this alternative is implausible based on analysis of inter-trial amplitude distribution. As explained in Supplementary materials 2, ERPs based on average amplitude and ERPs based on median amplitude over trials were very similar.

It is also possible that participants become experts in the stimuli by the end of a long experiment. Visual sensitivity might accumulate with visual experience. An SPN might not be considered automatic if it were only present on later trials that benefit from tacit perceptual learning. However, our ERPs did not systematically change as the experiments progressed. This is also explained in Supplementary materials 2.

11.3. *ERP difference between dark and light elements*

All experiments used stimuli with two luminance levels. This allowed us to compare luminance sensitivity across tasks. When participants were attending to luminance in Experiment 2, there was a significant late difference between light and dark waves from 300 to 400 msec at the posterior cluster [PO7, O1, O2 and PO8] [$M = .452\ \mu V$, $t(39) = 3.655$, $p < .001$, $d_z = .578$, Fig. 15A]. A comparable luminance difference was significant in Experiment 4, 6 and 8, but not in Experiments 1, 3 or 7 [Main effect of Experiment, $F(7,336) = 2.574$, $p = .013$, $\eta p^2 = .051$]. We caution that the analysed interval was not chosen a priori, so these effects require replication.

There are no obvious explanations for why some tasks inhibit luminance processing better than others. From this analysis, we can conclude that regularity is processed more readily than luminance in our stimulus set. In fact, this observation may generalize widely. After all, luminance can change with lighting conditions and must often be ignored when perceptually interpreting the retinal image. Meanwhile spatial relationships between elements must often be detected. Full treatment of results from all datasets are in Supplementary materials 3.

12. Discussion

Previous research has suggested that the response to reflectional symmetry in the extrastriate cortex is task independent (Höfel & Jacobsen, 2007; Makin et al., 2020). The current project confirmed this with eight new experiments. This apparent automaticity is consistent with microelectrode studies, where single neurons in anesthetised monkeys still fire in response to symmetrical gratings (Gallant et al., 1996).

This research program embraced the falsificationist idealisation of the scientific method. This holds that no amount of confirmatory evidence can establish that a theory is true, but one piece of disconfirmatory evidence can establish that a theory is false. Scientists thus seek disconfirmatory evidence. We have theory that the brain always responds to high W symmetry, whatever the task. We thus searched for tasks where the brain *does not* respond to high W symmetry. We did not discover any such 'black swan' tasks. However, it remains a logical possibility that they exist.

This work extends the symmetry literature in several ways. This was the first SPN project to systematically vary luminance discrimination task difficulty (Experiments 2 and 3). We found that the SPN was unexpectedly enhanced in the more difficult luminance discrimination task (Experiment 3). This is perhaps because participants had to pay more attention to the stimuli. Before Experiment 4, we ran a behavioural experiment based on the classic Mack and Rock (1998) studies. This confirmed that changes between symmetry and asymmetry are seldom noticed without attention. However, the same cross aspect ratio discrimination task did not abolish the SPN (Experiments 4 and 5). Experiment 6 found an SPN when symmetry was potentially distracting, rather than merely irrelevant. Next, Experiment 7 found that classification of superimposed negative words did not block symmetry processing. We now have less confidence in this finding from Rampone et al. (2014). Finally, Experiment 8 built on well-established facts about the visual cortex. Orientation tuned channels are connected by lateral inhibition. It was thus plausible that attention to oblique orientations would inhibit representation of the cardinal symmetry axes and abolish the SPN. However, this was not found. There was still an SPN in Experiment 8.

In a related set of experiments, Makin et al. (2020) compared SPNs from five tasks. A similar parametric SPN response was similar in four of them, and this selectively enhanced during regularity discrimination. We again found that SPN was enhanced by regularity discrimination in Experiment 1, replicating Makin et al. (2020). However, amplitude was not uniform across the other 7 experiments. In fact, it ranged substantially, from −.51 to −1.41 μV. Makin et al. (2020) had suggested that there is a default SPN response in all tasks except regularity discrimination, but now we find more evidence of modulation.

The task effects found here were much larger than the average .4 μV estimated by regression analysis of the SPN catalogue (Fig. 1B and Supplementary Materials 1). This can be explained by the relatively short 300 msec presentation duration. In most SPN experiments stimuli are presented for at least 1000 msec, so participants have plenty of time to shift selective attention from one visual dimension to another within each trial. Task relevant perceptual and cognitive operations could happen different times on different trials, and still leave spare time for spontaneous task irrelevant symmetry processing. We propose that the magnitude of task effects on SPN amplitude is inversely related to stimulus duration. This prediction will be systematically tested in future research.

All claims about the automaticity and preattentiveness of symmetry perception should be qualified by specifying the type of symmetry in question (Makin et al., 2023). What is true of high W symmetry may not be true of low W symmetry. Furthermore, what is true of reflectional symmetry might not be true of rotational or translational symmetry, even when W is matched. Moreover, reflectional symmetry with horizontal or vertical axis orientations may be detected more readily than reflectional symmetry with oblique axis orientations (Wenderoth, 1994). Such considerations are important when interpreting inconsistencies in the literature. For instance, Kimchi et al. (2016) and Devyatko and Kimchi (2020) both present evidence that symmetry detection is not automatic and preattentive, but this claim may only hold true for less salient forms of symmetry.

While we often discuss conditions for preattentive regularity *detection*, many experiments measure conditions for preattentive *discrimination* between more and less regular stimuli. The prevalence of preattentive discrimination may depend, in part, on the nature of the less regular stimuli. This also limits generalizability. For example, our results may not generalize to conditions where the less regular stimuli have a repetitive, tiled structure, such as the P1 exemplars used in wallpaper pattern research (Kohler & Clarke, 2021; Kohler et al., 2016).

When considering generalizability, we make a crucial distinction is between *retinal* and *extraretinal* symmetry. Most experiments, including those reported above, present 2D symmetry in the frontoparallel plane. This kind of stimulus projects a symmetrical image onto the retina. However, during naturalistic viewing, symmetrical objects are often seen from perspectives that distort symmetry in the retinal image (Sawada & Pizlo, 2008). Participants can detect perspective symmetry, albeit with some modest performance cost (Bertamini et al., 2022; Szlyk et al., 1995; van der Vloed et al., 2005). This suggests the extrastriate symmetry network can sometimes go beyond the image and achieve an extraretinal representation (this may also be termed an 'allocentric', 'view-invariant', or 'post-constancy' representation). Unlike retinal symmetry representations, extraretinal representations may only be constructed when they are task relevant (Keefe et al., 2018; Makin et al., 2015; Rampone et al., 2019).

An advantage of these experiments was the relatively large sample sizes. Forty participants were recruited in Experiments 1 to 6, and 52 participants were recruited in Experiments 7 and 8. In contrast, median sample size in the SPN catalogue projects was just 24. Makin et al. (2022) estimated that −.5 μV SPNs have a typical Cohen's d of −.469, and therefore a sample of 24 participants gives statistical power of just 60%. A researcher might run an underpowered SPN study, miss a true effect, and then interpret the null result as evidence of absence. With this flawed but common approach, one might conclude that tasks like ours had blocked symmetry processing and abolished the SPN in some tasks. However, this would be the wrong conclusion.

In summary, the extrastriate cortex seems highly receptive to reflectional symmetry in the image. This symmetry-vigilance could be adaptive. Reflectional symmetry plays a role in object detection and figure-ground segmentation (Mojica & Peterson, 2014), and presumably symmetry aids such routine visual operations even when we are not attending to it overtly. Reflectional symmetry in the retinal image is also biologically relevant. It is a cue indicating that another person or animal is facing you and may thus be aware of your existence. This is a special state of the world which may elicit specific emotions and behaviours (Tyler, 1995). Furthermore, human infants preferentially fixate reflectional symmetry at 4 months of age, indicating innate sensitivity (Bornstein et al., 1981, 2023; Pornstein & Krinsky, 1985). We propose that innate symmetry detectors in the extrastriate cortex are activated whenever double axis reflectional symmetry is present in the retinal image.

Transparency and Openness Promotion (TOP) statement

We report how we determined our sample size, all data exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study.

This paper reports data from **Project 41** of the complete Liverpool SPN catalogue (https://osf.io/2sncj/). Here the EEG data is available at various levels of granularity.

Anyone wishing to use the catalogue and understand the folder structure can start with the *beginner's guide* (https://osf.io/bq9ka/). This provides a tutorial on how to use our Matlab codes for data processing and visualization.

A priori data exclusion criteria were pre-registered on aspredicted.org (see https://aspredicted.org/hh3v8.pdf and other pre-registrations in this 'Mack and Rock Series' Folder).

Predictions for each experiment and a prior pre-processing plans are also listed here.

PDFs of these pre-registrations are also available within a subfolder within Project 41 in the SPN catalogue on OSF (https://osf.io/2sncj/). Here the names map onto the Experiment names in the paper.

Our a priori sample size decisions are described in the power analysis section 2.5.

As planned, we excluded trials where amplitude exceeded ±100 μV at any electrode.

As planned, we replaced participants where fewer that 50% of trials remained after data cleaning and trial exclusion.

Our analysis was based on pre-registered spatiotemporal clusters. The electrodes were PO7, O1, O2 and PO8 and time windows were 250–400 msec. All post hoc analyses, with different time windows, are clearly labelled as such.

Open practices

The study in this article has earned Open Data, Open Material and Preregistered Badges for transparent practices. The data, material and preregistration reports used in this study are available at: Project 41 at https://osf.io/2sncj/.

CRediT authorship contribution statement

Alexis D.J. Makin: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ned Buckley:** Writing – review & editing, Project administration, Conceptualization. **Emma Austin:** Writing – review & editing, Project administration, Conceptualization. **Marco Bertamini:** Writing – review & editing, Methodology, Conceptualization.

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Supplementary data

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